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PERMAFROST TUNNELING BY A CONTINUOUS MECHANICAL METHOD

George K. Swinzow

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CORPS OF ENGINEERS, U.S. ARMY
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PREFACE

This report was prepared by Dr. George K. Swinzow, Geologist, of the Construction Engineering Research Branch (Mr. Edward F. Lobacz, Chief), Experimental Engineering Division (Mr. Kenneth A. Linell, Chief), U.S. Army Cold Regions Research and Engineering Laboratory. It was published under DA Task 1T062112A13001, *Cold Regions Research – Applied Research and Engineering.*

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PERMAFROST TUNNELING BY A CONTINUOUS MECHANICAL METHOD

by

George K. Swinzow

INTRODUCTION

Purpose

This research was part of an effort to investigate methods of subsurface excavation for military installations in perennially frozen ground. Special emphasis was given to studies of the permafrost, its interaction with man's underground activity, and the properties of the tunnels, such as deformation, natural air flow, feasible types of ventilation, and the thermal regime.

For the purpose of this paper, permafrost is defined as unconsolidated soil such as alluvium, moraine, sand, silt or gravel deposits cemented by ice. As long as it is frozen it may be very similar to such rocks as conglomerate, sandstone, siltstone, etc. Usually the pore ice cement remains solid to temperatures very close to 0C.

The capacity of permafrost to absorb high velocity shocks without excessive shattering is attractive for military purposes (research on this is presently in progress). Roofs of tunnels and rooms excavated in permafrost are easily made safe and are relatively stable under explosive shock loads. Relative ease of excavation and the fact that the internal temperature is always appreciably higher than the air temperature during the arctic and subarctic winter mean that tunnels in permafrost are effective weather shelters.

Over the years man has developed three methods of frozen ground excavation: steam points, high pressure water jets, and explosives, used in hard rock tunneling. The explosives method was applied, tested and modified for use in permafrost during a special research program in Greenland (Abel, 1960; Swinzow, 1964).

Excavating a test tunnel in permafrost and studying the continuous mechanical tunneling method in this environment were the prime objectives of this study. A further objective was evaluation of the subsurface opening as a shelter, storage space, and site for military activity. Further, the tunnel provided opportunities to conduct geological, paleogeographical and rheological studies of an important type of permafrost. This report concentrates mainly on the tunneling method, the process of cutting frozen ground, and some general properties of the tunnel.

Mining classification of permafrost

Tunneling in "warm" unfrozen rock is a highly developed art. The engineer confronted with such a task may confidently predict costs and time, depending upon the type of strata, lithology and ground water conditions. However, relatively little is known about tunneling in permafrost.

To establish a "first generation" basis for planning an excavating, mining or tunneling operation in permafrost, we may regard two aspects of it: 1) properties to expect in any permafrost regardless of composition, and 2) properties of the particular permafrost deposit to be worked, such as ice content, mechanical composition of constituent minerals, and temperature.

In general the mining engineer can expect no water problem as long as tunneling proceeds in the frozen layer (not at its top or bottom). He will encounter temperatures below the melting point that fluctuate only slightly over the seasons. He may expect the winter temperature to be considerably lower outside than in the tunnel.

The particular deposit of permafrost may affect the excavation by having more or less ice cement, more or less coarse soils and boulders, and lower or higher temperatures. All these factors affect the operation and must be known in advance.

To predict difficulty and the extent of needed effort, one may begin by setting up a classification framework. The proposed classification (Table I) is based on arbitrarily set boundaries of the three main parameters: temperature, ice content and mechanical composition.

Table I. Mining engineer's classification of permafrost (proposed).

Temperature	*Ice content*	*Size of material*
Cold -7 to -10C (19 to 14F)	High	Fine
		Coarse
	Low	Fine
		Coarse
Intermediate -4 to -7c (25 to 19F)	High	Fine
		Coarse
	Low	Fine
		Coarse
Warm -0.5 to -4C (31 to 25F)	High	Fine
		Coarse
	Low	Fine
		Coarse

The arbitrary parameters are arranged in three columns in the order in which they cause increasing difficulties. The first column begins with cold permafrost and ends with warm permafrost. The limits are -10C, a temperature to be expected at very few sites, and -0.5C, above which hardly any stable permafrost exists. Ice content is regarded in terms of the degree of saturation. Relatively dry permafrost may be excavated more easily than ice-saturated material, but roof stability may decrease with decreasing amounts of ice cement. Furthermore there is the problem of maximum span. It is obvious that in dry permafrost one should allow for less span than in a fully saturated permafrost. The third column reflects the composition. An abundance of boulders, especially metamorphic and igneous material, leads to difficulties of a primary nature, e.g. hard rock drilling and unfavorable powder ratios with overburden. In column 3, the upper item in each temperature range is always the more favorable for excavation.

The table shows that a cold permafrost consisting of fine material strongly cemented by abundant ice is more advantageous than warm, undersaturated material consisting predominantly of large boulders. The table is intended to predict technical difficulties and assist a mining engineer in planning and selecting the excavation method for a given location. For example, a

location in the northern archipelago of Canada with cold permafrost with intermediate to high ice content, consisting of predominantly bouldery material, requires modified hard-rock excavation methods such as those described by Swinzow (1964). Roof instability problems are insignificant and can be remedied by application of quick back-freezing slurries. Overbreak and slabbing can be handled similarly. The engineer can probably expect a somewhat higher powder ratio, but he may cross most of the timber and all of the concrete off his list.

At the other extreme is a warm permafrost with low ice content and coarse boulders. There are problems with all engineering features. The rate of advance may become low due to overbreak. An unstable roof requires a large amount of timber work while man and machine are jeopardized by thawing in the roof.

ENVIRONMENT

Location and strata

The site of the Alaska Experimental Permafrost Tunnel is an abandoned gold dredging field. During mining operations the central part of Engineer Creek Valley was stripped of its overburden of perennially frozen silt and the underlying gravel was dredged for gold and dumped in small hills, dry and unfrozen. The edge of the field is a steep, unstable cliff of overburden. At its foot the gravel was smoothed out and a mining camp erected. The portal was constructed in the steep cliff at the boundary of the gold field and the tunnel was driven into the perennially frozen silt (Fig. 1).

The perennially frozen Fairbanks silt, first described by Mertie (1937), is supersaturated and contains large lenses, wedges and veins of ice. The deposit is stratified; streaks of sand (fine and coarse) and gravel are common throughout the tunnel. A distinct characteristic of the tunnel is its odor, derived from partially preserved organic material in the frozen silt. The presence of abundant partially preserved animal and plant material indicates the possibility of syngenetic* origin. The microscopic appearance of the silt's fabric is that of an open packing impossible to achieve by ordinary sedimentation. Figure 2 is a polished section of a frozen sample made by a technique similar to that used in metallurgy. The blank portions represent clean ice. Note that the packing is open in the coarser as well as in the clay-size fraction.

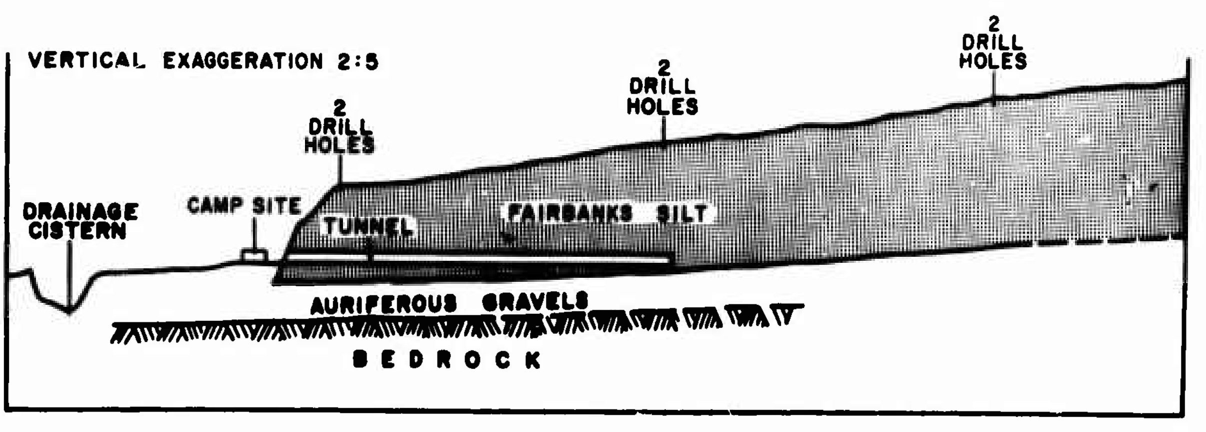
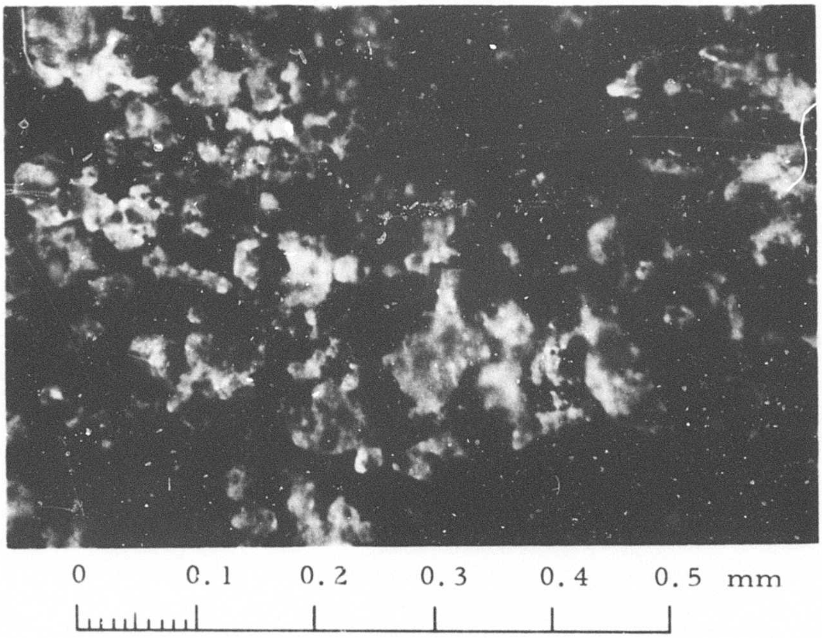
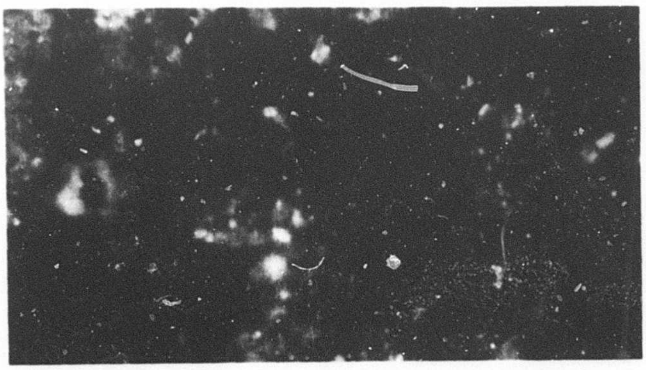


Figure 1. Schematic geological cross section along the axis of the tunnel.

* Permafrost formed during deposition.



a. *Section with predominantly coarse particles.*

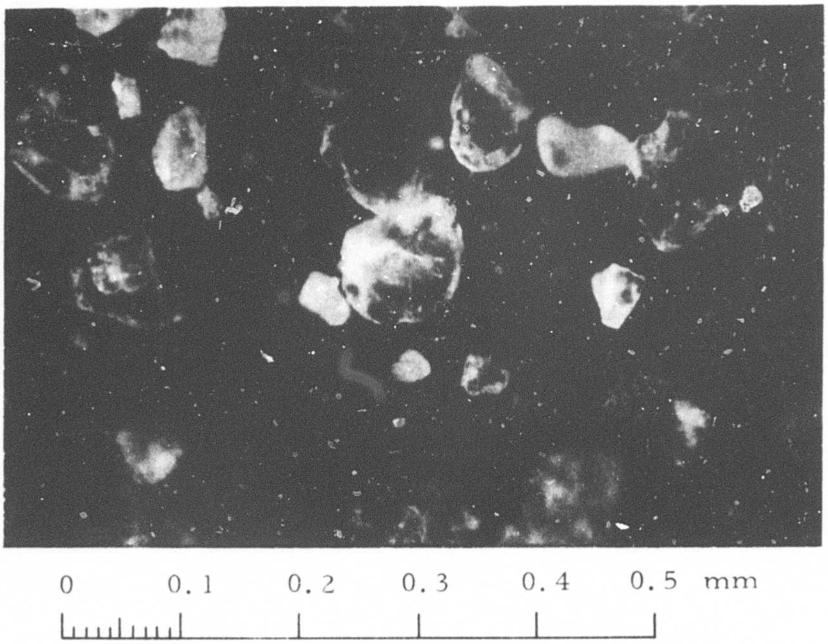


b. *Section with mainly fine, clay-size particles.*

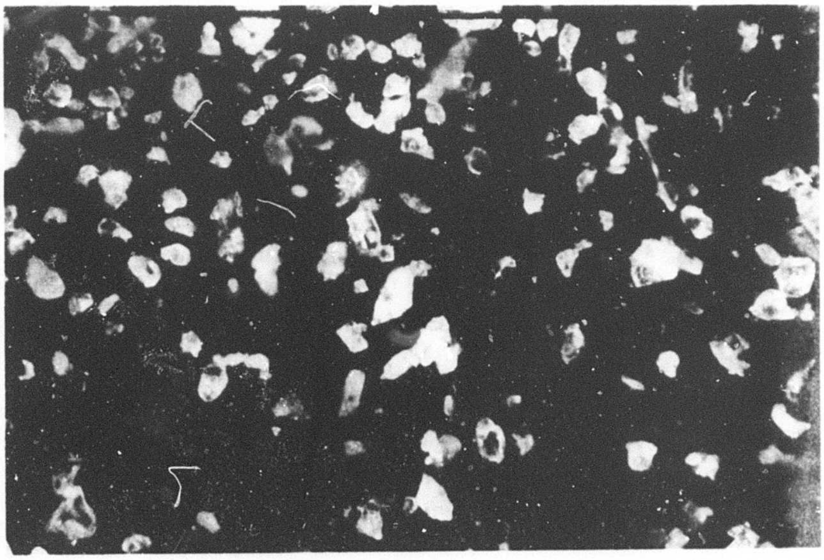
Figure 2. Polished sections of Fairbanks silt photographed in reflected light (Ultropak method).

Figure 3 shows slides of two typical ingredients of Fairbanks silt. The 0.1-mm particles (Fig. 3a) are predominantly micas, such as biotite, muscovite and phlogopite, with only a few other minerals like quartz and the feldspars. Figure 3b, an assemblage of 0.01-mm grains, contains most of the quartz and feldspars with a few other minerals. The grains smaller than 0.1 mm were essentially monomineralic and apparently very little mechanical rounding had occurred (the particles were angular and unweathered). Clay-size material (not illustrated) was mostly sericite mixed with ordinary clay minerals such as montmorillonite and kaolinite.

Vertical exploration drilling, as well as tunneling, disclosed inclusions of stones in amounts increasing with depth. These stony inclusions are, as a rule, of very low sphericity and vary from a fraction of an inch in diameter to cobble size (4 to 7 in.). Figure 4 is an example of an area with large stones. At the time the machine was excavating this area, about 74 ft from the portal, the structure occupied the cutting face, presenting a similar pattern in a plane perpendicular



a. *0.1-mm particle - predominantly micas.*



b. *0.01-mm particle - quartz, feldspars, occasional garnets.*

Figure 3. Microslides of Fairbanks silt (Ultropak illumination).

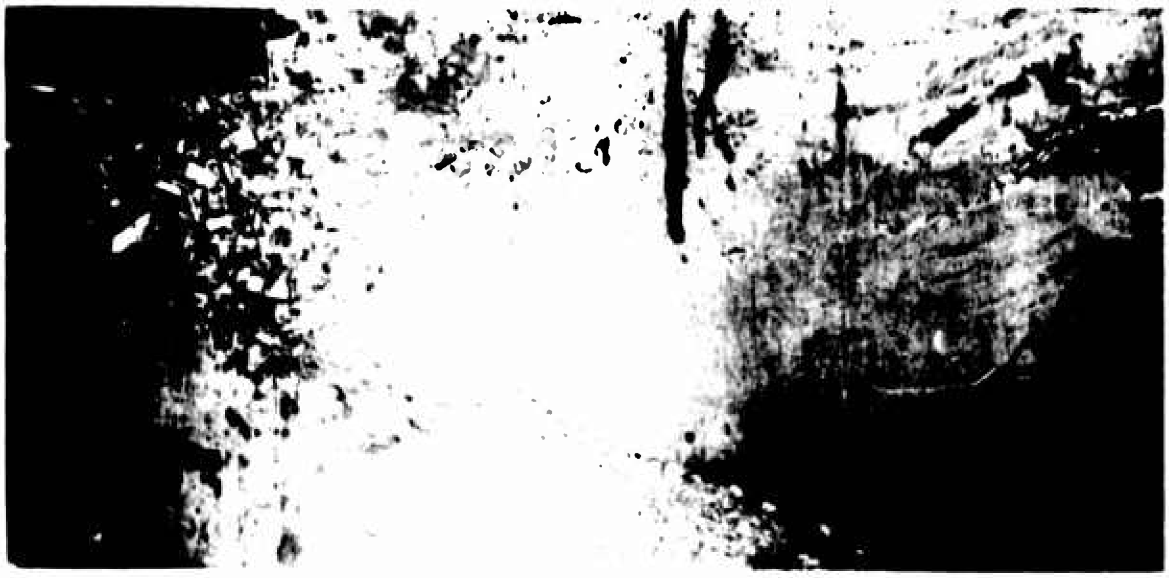


Figure 4. Structure of stone inclusions 74 ft from portal. Scale in center of photo: 1 in. = 1½ ft (approximately).

to that of the picture. The impression was of an excavated asymmetrical sorted stone polygon of the type described by Corté (1962). The gravel underlying the Fairbanks silt is a very angular, inhomogeneous material with very low sphericity. Generally its appearance is similar to the material exposed in the tunnel (Fig. 4). The Fairbanks silt stratum does not have a sharp lower boundary, but becomes gradually richer in rock fragments. It is possible that the "gravelly" exp ures in the tunnel are results of frost action upon the auriferous gravels during the silt deposition.

The exact mode and rate of deposition of the Fairbanks silt cannot be explained satisfactorily. Available literature suggests a variety of origins. Péwé (1955) conducted geological mapping of the area and hypothesizes that the "upland silts" as he calls them were deposited by an eolian process. He includes the process of loess formation in the depositional cycle.

Taber (1943) presents the stratigraphic position of the silt as a whole including its frozen parts.

The permafrost tunnel disclosed strata in the Fairbanks silt indicating discontinuous deposition rates with patterned ground and ice wedge formation. Figure 5 is an example of a probable former "daylight" surface such as is usually displayed by hummocky tundra. Such a formation would be possible only during a break in soil deposition. Numerous ice wedges, autochthonous ice masses and segregation veinlets also indicate interrupted deposition or changes in its rate (Fig. 6). Detailed study of plant remnants in the tunnel may lead to evidence of climatic changes during the deposition of Fairbanks silt. Figure 7a shows a stratum rich in tree-root remnants; Figure 7b shows an ice wedge buried by subsequent deposition.

Thermal environment

Geographically the Fairbanks area is near the southern border of discontinuous permafrost. The mean annual temperature in the area is very close to -3.3C. Freezing weather is remarkably prevalent. Normally a slight excess of days with frost over thawing weather is sufficient for

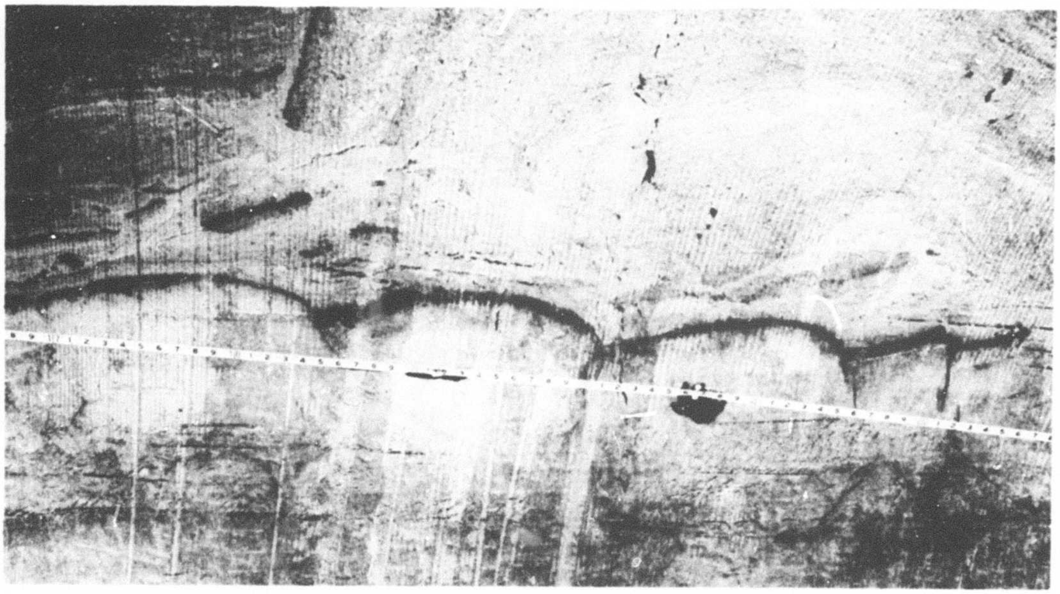
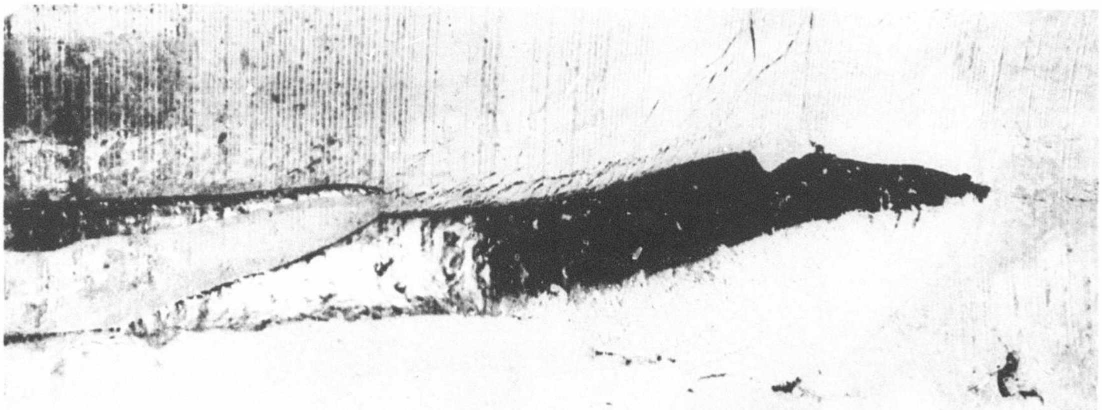


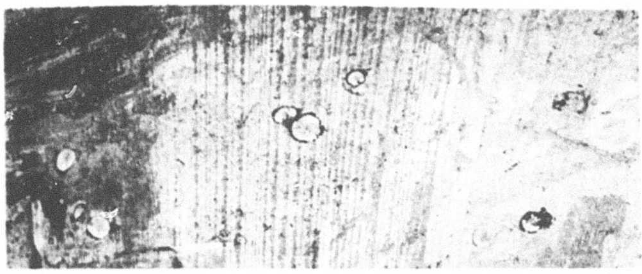
Figure 5. Patterned organic inclusion layer. Probable origin: buried tundra humps.



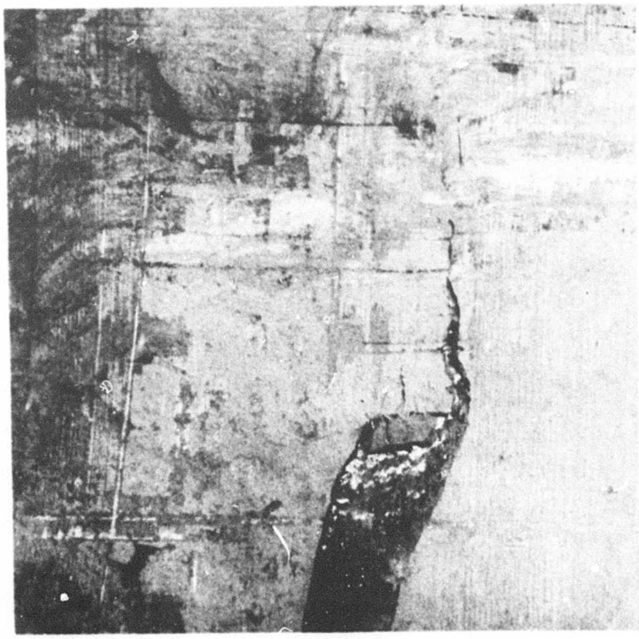
a. *140 ft. Ice inclusion with truncated top.*

b. *150 ft. Ice veinlets and flat lens.*

Figure 6. Some types of ice appearing in the tunnel.



a. *Section at 60 ft. Tree roots preserved in permafrost. Gravelly beds visible in upper left corner.*



b. *Ice wedge at 124 ft.*

Figure 7. Some details of tunnel wall.

permafrost formation. The Fairbanks area has a ratio of freezing degree-days to thawing degree-days of approximately 1.7:1. One would expect to find continuous permafrost with a temperature about the same as the yearly average. On the contrary, the permafrost of the Fairbanks area is warm (minimum temperature around -2C) and discontinuous. One reason for this might be an increased geothermal flux of which there is some evidence in the area. However, as far as could be determined, the geothermal gradient in this region has never been studied with sufficient accuracy to explain an apparent anomaly.

The area is relatively dry - about 30 cm of precipitation per year. The snow cover is up to 100 cm thick.

Physiography

The permafrost in the Fairbanks area is discontinuous. Hills and ridges are as a rule unfrozen; southern slopes are unlikely to have permafrost while the greatest depths are in narrow valley floors. One possible explanation for this is that there are frequent winter thermal inversions in the area. Weather records from Fairbanks as well as from the tunnel site show that when air temperatures at higher elevations are as high as -20 to -30C, valley floors may be at -40 to -50C.

Normally the borderline between permafrost and unfrozen ground is not a simple vertical cutoff. It is either a progressive thickening of the active layer to a point where it only rarely fuses with permafrost at the time of greatest winter frost penetration, or the lower boundary of the permafrost becomes progressively shallower until it reaches the winter depth of freezing.

Preliminary field explorations disclosed both. Moving up the valley slope approximately along the axis of the tunnel, we found, by drilling, a progressive thickening of the seasonal frost layer together with thinning of the perennially frozen layer until both met, which was considered to be a local border of the permafrost area. In some cases there was more than one frozen layer in only a few meters of depth. It is apparent, therefore, that the perennially frozen silt body must be in the form of a concave-convex lens in cross section with neither surface parallel to the topographic profile.

For further discussion concerning details of the tunnel site geology, geomorphology and cryopedology, see Sellmann (1967). McCoy (1964) gives a series of gradation curves reflecting the mechanical composition of the frozen silt as well as the limits of its changes.

SELECTION OF MINING PRINCIPLE

The tunnel site is 11 miles north of Fairbanks near the Steese Highway. The local permafrost is warm (around -1C), fine grained and has a high ice content (up to 65% by volume). Preliminary geological site exploration disclosed possible severe difficulties for the rock drill and a low response to explosives. It was therefore only logical to scrutinize one of the continuous mechanical methods used in the coal industry. Parameters for selection of a suitable machine were to be weight, power requirements, and degree of mobility, together with initial cost. An additional point was the search for some novel principle with an obvious technical advantage.

An extensive survey was made among the existing continuous mechanical mining systems. Six machines were selected for final comparison. Their fundamental properties are summarized in Table II.

On the basis of the data in Table II the Alkirk Continuous Cycle Miner (Fig. 8) was selected. Its relatively low weight constituted a major logistical advantage. Its power consumption was also advantageous, and it employed a novel principle, the so-call "pilot pull principle."

Any continuous mechanical miner must incorporate four functions: 1) locomotion (tramming) to move toward the face; 2) sufficient thrust against the face for the cutting teeth to dig into the material; 3) disintegration of the material at the face by means of continuous motion of the cutting tools; and 4) delivery of the cuttings away from the face to a place where they may be conveyed to the surface.

Table II. Selected properties of six mechanical mining systems.

System	Approx. basic price (1962)	Gross weight (tons)	Remarks
Foundation Co. of Canada	$ 75,000	60	Applied in Toronto in soft shale and limestone. Breakdown reported.
Robbins Cont. Miner	200,000	35 (basic)	Machine successful in soft formations. Large power requirements.
Goodman System (Type 426)	150,000	52	Used successfully in potash mining. Power requirement: 600 hp.
Joy Mfg. System (2BT-2)	150,000	40 (basic)	Machine would need to be redesigned. Requires 600 hp.
Alkirk Pull Principle	150,000	12.5	Machine applies a unique pull principle. Requires 225 hp.
Kirk-Hillman	150,000	est. 30	No record of successful application available. Power requirements unknown.

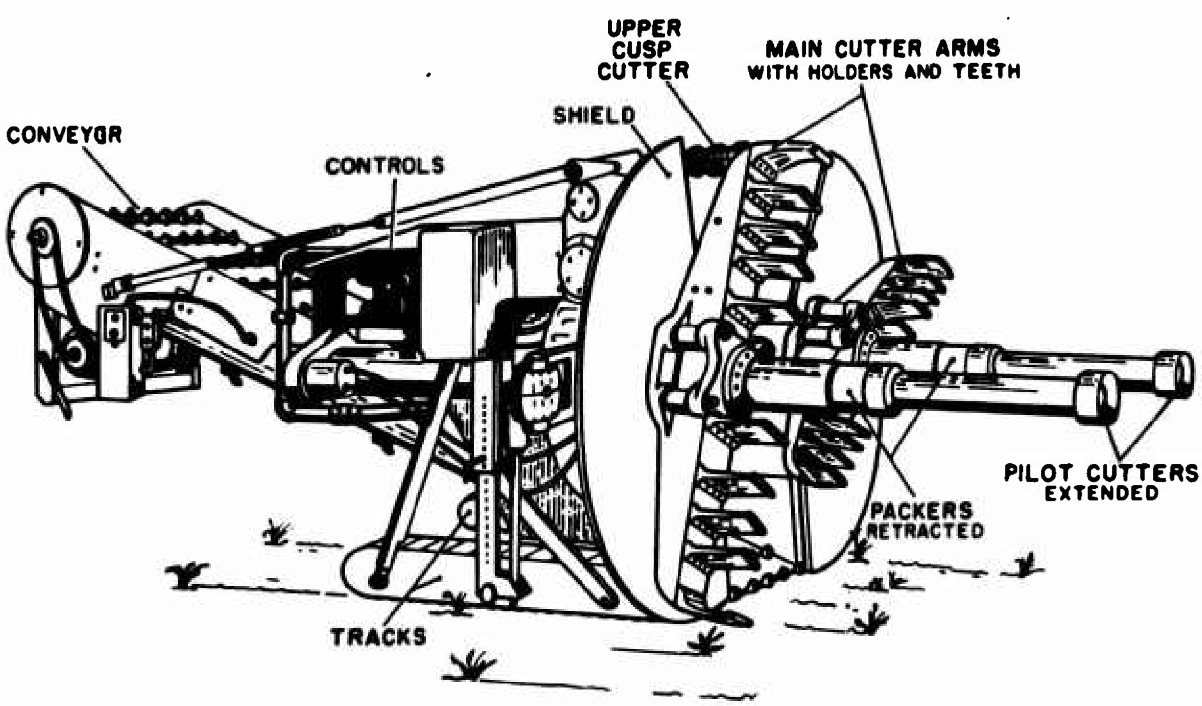


Figure 8. The Alkirk Continuous Miner

To accomplish the second function the Alkirk miner employs the unique twin pilot-pull principle. Two 8-in. pilot cutters drill two anchor holes into the rock face and are fastened into them ahead of the machine. After the pilot holes are drilled and the anchoring packers set, the main cutting arms are engaged and rotate in opposite directions. The machine then moves into the face by pulling against the two anchors. The machine does not rely upon its own weight for forward thrust nor does it need hydraulic wall rams or excess traction force. The two main 7-ft-diam cutting arms rotate on centers 5.5 ft apart so that the circles they scribe on the face overlap. The two cusps left on roof and floor are removed by two arrangements: an upper rigid-axis cusp cutter and a lower cutting link-chain conveyor armed with drag bits. The conveyor also removes the cuttings to the rear of the machine for tramming out.

Below are given some technical data on the machine necessary for further discussion. More details of a functional nature are given by McCoy (1964).

Dimensions:

Diameter of miner cutters	7 ft
Diameter of pilot borers	8 in.
Distance between centers	5 ft 6 in.
Work stroke, maximum	5 ft

Cut dimensions:

Vertical	7 ft
Horizontal	12 ft 6 in.

Drive:

Liquid-cooled electric motor, 200 hp, 1800 rpm, 440 v, 60 cycle, 3 phase explosion proof, 200% overload.

Main cutter drive:

Worm gear type, two speed: 10-and 15-rpm pilot cutter drives.
Hydraulic motor speed about 110 rpm.

Track drive:

Independently controlled hydraulic motor; infinitely variable speed; 0 - 30 rpm forward and reverse.

Conveyor drive:

Electric motor, 25 hp, 440 v, 60 cycle, explosion-proof.

Functional control:

Six hydraulic motors, hydraulic selector-valves, infinite control, pressure checks, reverse flow, two pressures - high and low.

Heat exchanger system:

Oil to oil, oil to antifreeze, antifreeze to air.

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Oil to oil, oil to antifreeze, antifreeze to air.

The whole arrangement of mining equipment in the tunnel is shown schematically in Figure 9. Table III summarizes pertinent haulage data.

Table III. Haulage data

1. Requirements to mine one cycle

Nominal time*	15 min
Tunnel length	0.61 m (2 ft)
Volume of material in place	3.9 m^3 (5.1 yd^3)
Expansion factor	2.45
Volume of material to be moved in one cycle	9.51 m^3 (12.5 yd^3)
Average time to load one shuttle car	6 min
Average time to unload one shuttle car	4 min

2. Ratio of mining time to total operation time

0 ft	0.500
50 ft	0.428
100 ft	0.375
150 ft	0.316
200 ft	0.250
250 ft	0.231
300 ft	0.214
350 ft	0.207

* Time without hauling trip delay.

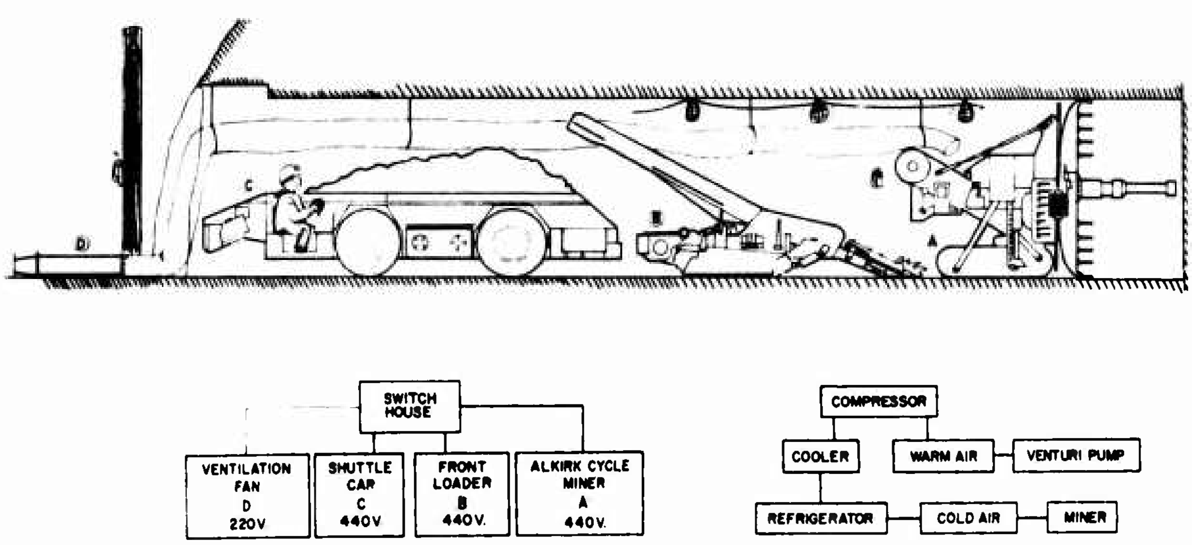


Figure 9. The arrangement of equipment in the tunnel.

Operating the machine required an average of 113.8 kilowatt-hours per linear meter of tunnel (34.7 kwhr/ft). This included all equipment: miner, front loader, shuttle car and ventilation plant. The consumption varied from 82 kwhr/m to 208.3 kwhr/m (25-63.5 kwhr/ft) owing to the need for long warm-up idling of cold equipment or idle run for adjusting and for packer slipping (see below).

All three machines in the tunnel operated on trailing cables. The shuttle car had a servo-mechanism-guided cable drum which would wind and lay out its cable unattended. The cables for the miner and front loader had to be brought forward manually, an operation requiring an estimated 5% of the total man-hours.

Operation of the miner requires 183 m^3 of air pressurized to around 8 atm (120 psi). The air is needed to remove the pilot bore cuttings and to cool the anchoring packers to ensure a firm hold. Ventilation to supply fresh air and remove heat generated by the machines was also needed for efficient operation.

The last step in the whole operation was dump handling. Normally there are three possible methods for dumping waste materials in a tunneling operation: dumping downhill with an ever-extending ramp, either parallel or perpendicular to the slope, conveying uphill (in this case the operation becomes a stage of haulage such as open pit mining); and handling the muck on grade level. The topographical situation at the tunnel site called for handling on grade. Several methods were tried:

1. Dumping individual shuttle car loads over a field about 70 × 140 m (200 × 400 ft) and spreading by bulldozer at the end of two shifts. This method was satisfactory since the following summer melting removed most of the material.

2. The gradual buildup of a 22° ramp by end-dumping from the shuttle car. Allowing the ramp to grow to a height of 1.5 m resulted in haulage delays. Such a ramp had to be removed with a bulldozer.

Function and performance

Framework of development. The framework of the present research was the search for and evaluation of rapid methods of permafrost excavation for military purposes. A new method incorporating the revolutionary pilot pull principle was selected and great attention was given to its performance and potential. Observations confirmed that pulling the machine into the face instead of relying on weight or having hydraulic rams working against tunnel walls results in a general lightening of construction, increased mobility and high performance rates.

It is emphasized that the test vehicle was a first generation machine with many mechanical deficiencies. The overall performance was found to be affected by both the machine's functions and deficiencies and the new environment - warm permafrost - in which it was working. The properties of the permafrost (warm, fine-grained, supersaturated) together with a tooth design and cutting speeds unsuitable for the material led to a situation where the pilot pull principle of face-crowd could not be shown to its full advantage.

With a continuously operating machine in combination with an adequate waste disposal system, the costs of a tunneling operation similar to the present one might very well be below those of any conventional mining system. It must be remarked, however, that cost in a military operation often becomes subordinate to mobility, speed, simplicity of operation, and relatively low weight.

Response of machine to environment. The pilot boreholes cut into the face at the beginning of each cycle are only 1 cm larger than the packers before expansion. Axial pressure on the packer rings expands them toward the walls of the hole providing anchorage. Since the fine-grained ice-saturated silt has a high temperature, very close to zero C, heat leaking along the pilot tubes was found to be warming it to a degree where rapid creep occurred.

Refrigerated compressed air was blown continuously through the packers but the benefit was only moderate and diminished as tunneling progressed. Once the anchors failed, it required 2 to 3 hours to cool the soil to a temperature at which it was capable of holding the packers in place.

The heat generated by the machine and rejected into the tunnel resulted in an additional ventilation requirement. A 12-in. collapsible hose was installed and outside air was blown into the tunnel. The hose terminated against an automotive radiator installed in the antifreeze circulation system of the Alkirk miner. However, the air traveling through the hose gained up to 3C, depending upon tunnel length. An increase in efficiency was noted with the installation of a 6-in. rigid suction pipe to remove air from the vicinity of the machine.

In general, ventilation demand in permafrost tunneling exceeds that otherwise needed, for its main purpose is removal of reject heat. Heat removal from a working machine by ventilation may be considered inefficient but no other methods are as convenient.

Table IV gives a rough estimate of ventilation needs at two different tunneling rates, made on the basis of power consumption.

Table IV. Ventilation demands for the Alkirk excavation system as related to ambient temperature and tunnel cutting rates.

	Ventilation demand	
Outside air temp	*Cutting rate (1 m/hr)*	*Cutting rate (2 m/hr)*
-10C	425 m^3/min	900 m^3/min
-15	275	550
-20	186	350
-25	155	275
-30	120	270
-35	100	200
-40	80	175
-45	60	150
-50	40	120

Table IV is not based on field data but on a simplified assumption that the machine rejected all its heat into the surrounding air which had to be removed at ever-increasing rates as the ambient temperature rose. Unfortunately, the experimental work did not afford either sustained cutting at either of the two rates or ventilation sufficient to remove the heat generated.

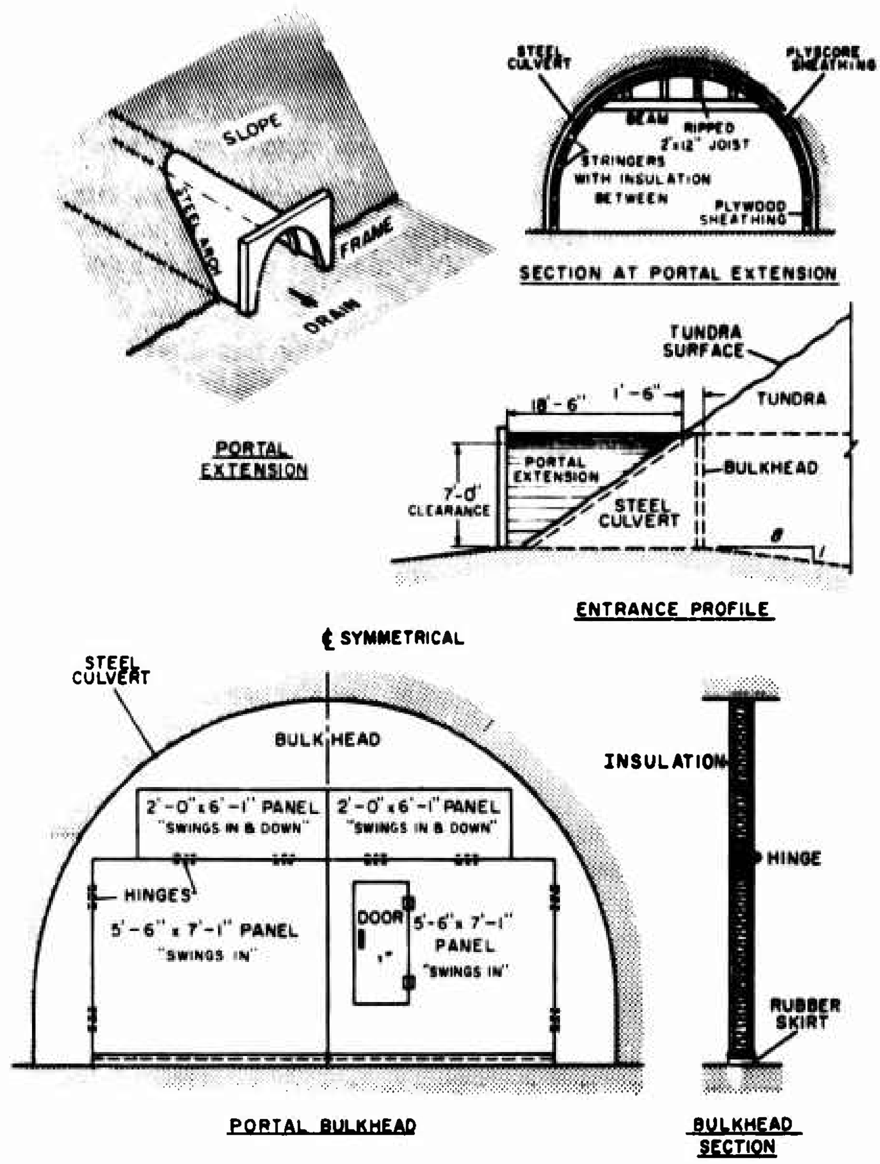


Figure 10. Portal structure

Special construction in permafrost tunneling

Portal. Portal construction, a stage separate from the rest of tunneling activity, is an important and inevitable part of any tunneling operation. Unlike conventional tunneling, a tunnel portal in permafrost has its function extended to summer heat protection.

For the Alaska Permafrost Tunnel, a vertical face was excavated into the slope and 5.4-m (18-ft) diameter corrugated steel culvert was inserted and placed against the face, insulated, and cut flush with the slope. Spaces were backfilled and then the cover part of the culvert was backfilled with gravel. The slope immediately above the culvert was protected by radial brine pipes for artificial freezing in case of a catastrophic thaw.

The steel culvert was extended by a semicircular wooden structure to deflect rain and any material sliding down the unstable slope. Inside the portal structure was an insulated wooden bulkhead with composite doors. Figure 10 shows the portal structure as it was built.

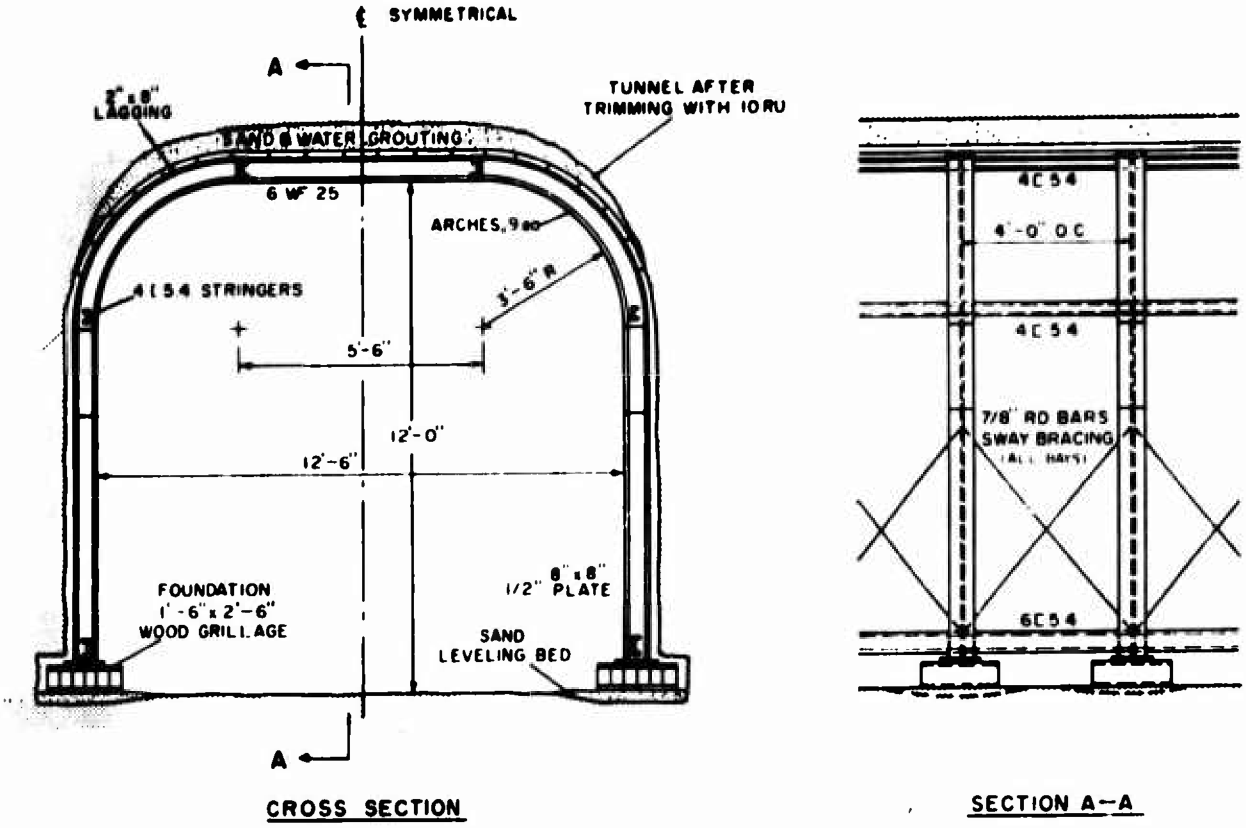


Figure 11. Arch roof supports.

Arches. To make the permafrost tunnel safer, nine welded steel arches of 6WF25 sections were installed in the first 8.6 m of the tunnel (Fig. 11). The arches were designed to yield rather than rupture should a full overburden load suddenly develop, and were intended to protect against roof settlement. The measure was an added safety feature for the specific case, since the tunnel was to be driven into an unstable man-made slope in an area where earthquakes are common. Standard yieldable mining arches were not used as the profile of the tunnel was incompatible. The narrow space between arches and permafrost was lagged with 2 × 8 timber and grouted with moist sand.

Tunnel configuration. Normally, a tunnel driven into a warm rock under conventional conditions is likely to be subject to water seepage or flood. For that and other purely mining engineering reasons, it is customary to design and to drive a tunnel at an upward gradient of a few degrees.

From the beginning of the operation, partially due to difficulties with horizontal and vertical alignment, the Alaska Tunnel was driven in defiance of that rule (see Fig. 12). Its shape differed from that of conventional tunnels in that it had a depression of the floor at the portal to accumulate cold air. It was hoped that this would result in colder permafrost near the portal which might have been beneficial since the oval section of the tunnel had to accommodate movement of men and machines. For convenience and safety the power cables, air hoses, and telephone lines were placed in slots cut longitudinally into the lower part of the tunnel. As an additional safety measure, a heat exchanger was placed in the tunnel at the highest point in the portal area. It was connected with a compressor installation to be used if the portal area became dangerously warm.

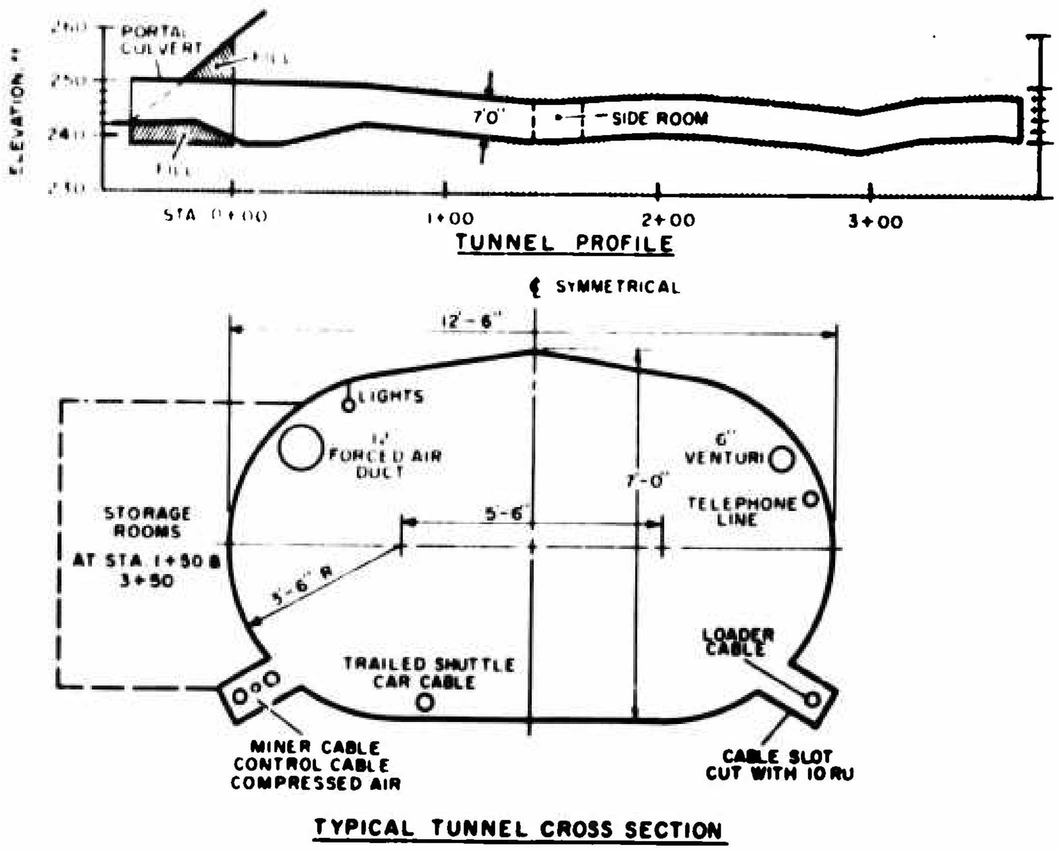


Figure 12. Profile and cross section of the Alaska tunnel.

PERFORMANCE OF THE MINER

Excavation by a continuous mechanical method

Potential performance of the machine. Observations on the operation of the machine led to the general conclusion that the Alkirk Continuous Miner is potentially capable of sustaining an excavation rate of several meters per hour. Remedy of certain structural and mechanical deficiencies (to be discussed later), the provision of heat removal, and an adequate supply of power and refrigerated compressed air are all prerequisites.

An adequate continuous haulage capacity is very important since without simultaneous debris removal the machine buries itself in its muck pile in a matter of minutes.

Observations on cutting strain and power consumption. One problem needing a special approach was observation of the dynamic cutting forces as related to power consumption, face pressure, pressures of hydraulic fluids, etc. This was done by means of strain gauges, pressure transducers and recording wattmeters in a system designed by G.A. Brewer (1965). The cutting force transducers consisted of a standard Alkirk tool holder, undercut at the proper place, and two strain gauge rosettes applied in a way that eliminated the possibility of mechanical damage and influence of thermal shock. The calibration was by application of known loads in the usual manner (Fig. 13).

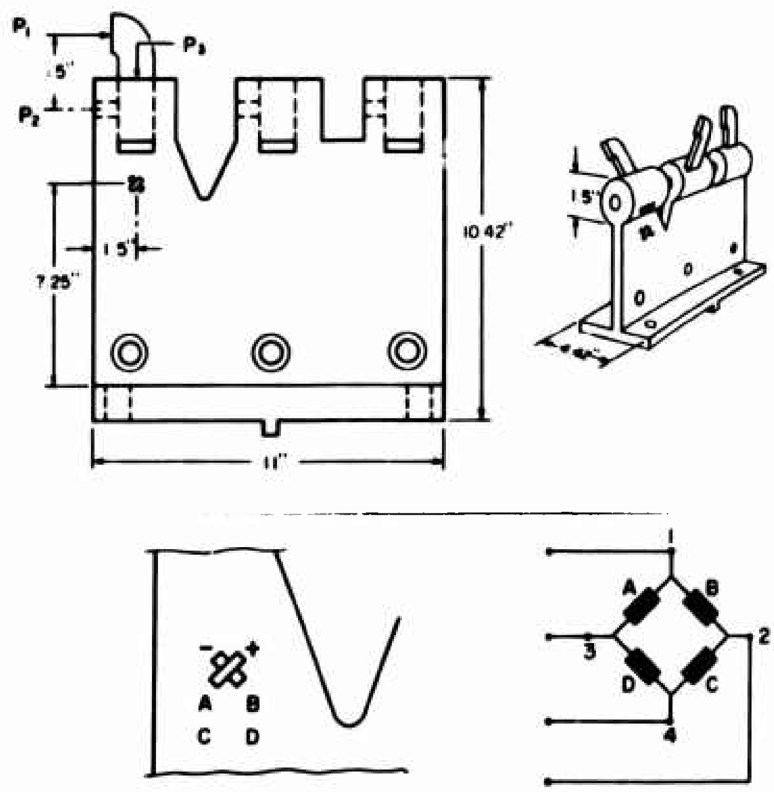


Figure 13. Cutting force transducer arrangement.

Since the Alkirk cutting tool revolves around a shaft the data from the load cells were transmitted by radio into the tunnel where they were recorded simultaneously with all other information.

The machine's hydraulic system was monitored by two GEC fast response resistance type pressure cells at the face pressure and packer pressure lines. Finally, power consumption was recorded at all stages of the investigation. The measurements were made by G.A. Brewer (1965) under contract with USA CRREL. He reports an average of 64 kw power consumption during cutting and 32 kw idling, packer pressure 1400 psi, face pressure (crowd) 500 psi, and a cutting force between 500 and 1100 lb.

During the miner operation, sharp peaks of face and packer pressure that could have been detrimental to the hydraulic system of the machine were recorded. Brewer expressed concern that high pressure surges are most probably the cause of numerous hydraulic leaks, C ring failures and line bursts.

Labor requirements. The personnel occupied with experimental tunneling consisted of two engineers, six technical personnel and the project leader. Normal production tunneling in a similar environment would require one mechanic, specially trained to operate the miner; one helper, doubling for outside work, such as compressor-plant help; one shuttle-car operator; one front-loader operator; and one general helper. An additional man would be needed to take care of outside work.

It is important to mention that trials showed that increasing manpower did not increase productivity. An extra mechanic on the crew did help during repair of the miner. Employment of more than two repair men is not beneficial owing to crowded conditions at the tunnel face.

Much depends on the crew's training. In addition to being a certified mechanic, the miner operator must have at least three months of specialized training. His helper must be a mechanic, who could be trained on the job. The shuttle-car and front-loader operators may be heavy-equipment operators who could be trained in the course of one day.

An experienced miner should operate the muck pile outside.

Other observations on the machine. Operation manuals, manufacturer's instructions and blueprints of the Alkirk Continuous Miner indicate a very complex hydraulic system which in the prototype machine under test was prone to frequent failure. Most frequent were air locks in valves, broken lines and fittings, failures in hydraulic pumps and motors, and fluid leaks in pilot tubes. Maintenance records for 30 shifts (about 22 hours actual mining) show 98 gallons of hydraulic fluid was lost. Specialized testing equipment and special training for the mechanics would have lessened lost time. Another deficiency of the hydraulic system, insufficient cooling of the fluid, resulted in overheating of pilots and soil, and slip of anchor packers. It seems plausible that the frequent line bursts and other failures were due to the extremely high peaks in hydraulic fluid pressure as observed and reported by Brewer (1965).

The failure of packers to provide support for crowd pressure was responsible for a large percentage of the mining time loss. As mentioned, the cause was cumulative: packer design insufficient for local permafrost, need for excessive crowding (see below), insufficient heat removal capacity, and frequent idling due to insufficient hauling capacity.

Two other construction deficiencies were a frequent source of delay during the main tunneling procedure. One was the tracks of the machine which were inadequate for walking on ordinary surfaces. The machine had to be moved on plywood to prevent tearing the tracks. In several instances tracks were damaged when a small foreign body such as a pebble became jammed between cleats.

Serious deficiencies were found in the alignment system. For correctional horizontal alignment, the design procedure requires application of additional face pressure on the cutter opposite the direction in which it is desired to turn. Besides being ineffective, this is detrimental to the pilot tubes and their oil seals. It was found that the only opportunity to change horizontal direction came at the end of the cycle. The pilot tubes were extracted, the machine was backed away from the face and realigned in a new direction, and new pilot holes were cut. At times it was necessary to plug and refreeze the old pilot holes. This technique permitted a correction of a few degrees at a time.

Vertical alignment presented more serious problems owing to the mechanism provided for it. The machine had a tilting device to raise or lower the cutting parts simultaneously. Figure 14a,b shows the alignment for horizontal cutting and a configuration for raising the centerline of the tunnel. The angle is exaggerated for clarity. Note that the dimension of the tunnel (a) is identical with that of the new tunnel, while tilting the overall size of the cut (b).

Attempts to raise the tunnel by the existing method resulted in binding the machine at the face, bending of pilot tubes and failures of the upper cusp cutter.

It appears that an arrangement similar to that used in snow millers (the Peter Snowmiller for example) would solve the problem. Figure 14c represents a proposed configuration for straight line cutting and Figure 14d shows the cutting mechanism lifted *parallel* to the axis of the tunnel. Figure 14e shows the configuration for directing the tunnel downward.

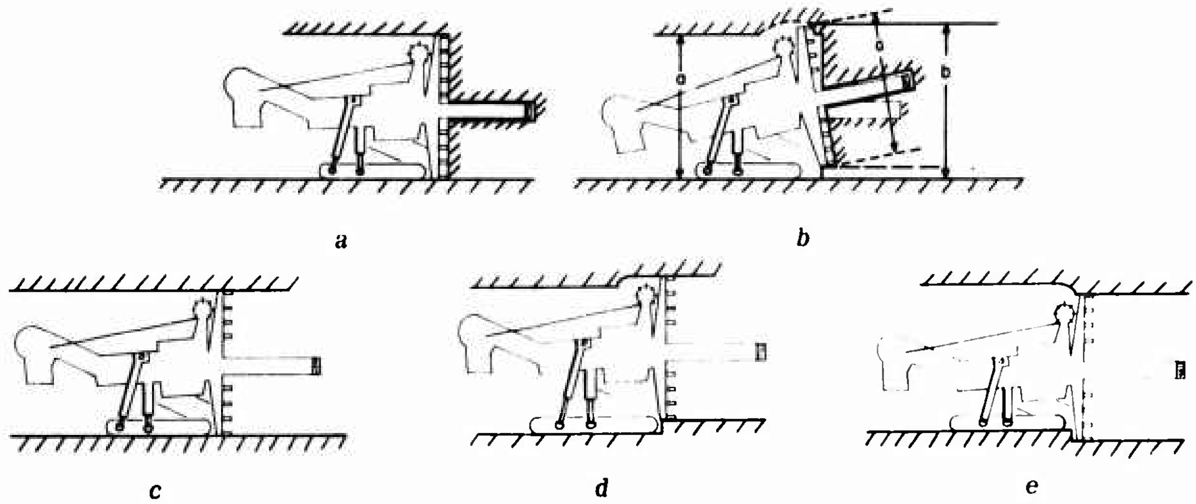


Figure 14. Existing and suggested vertical alignment principles.
a,b: Existing method, distances a and b unidentical.
c,d,e: Suggested mechanism: No change in tunnel dimensions.

Another solution would be to widen or narrow the tunnel diameter at will by 1 or 2 cm. The effect of such an arrangement would be much the same as that shown in Figure 14, d and e.

Cutting action

The main job of excavation was done by two circular counter-rotating windmill cutters set in position to cut most of the oval outline of the tunnel. The description that follows concerns the main action of the machine - the two cutting arms in circular motion.

The maximum cutting speed on the periphery of the two cutters is 67m/min (220 ft/min) at 10 rpm; all other parts of the cutters move correspondingly slower. The cutters are armed with standard drag bits (Fig. 15). The teeth on all four arms are positioned so that alternate passes over the face leave a system of grooves and lands (Fig. 16). The 2.4-cm-thick lands broke off from time to time, apparently without a notable expenditure of energy.

During an early tunneling stage an attempt was made to cut the whole face without leaving any grooves or lands (Fig. 17). This resulted in formation of fine cuttings, slow progress and overload of the machine. It was concluded that tightly spaced drag bits do unnecessary work, using additional energy to disintegrate the material excessively.

The following findings connected with the cutting process are based on direct measurements and experimentation.

To cut grooves wide enough for the tool holder, a single bit of 5-cm edge width was originally used. The tungsten carbide edge soon began to chip in several places, resulting in an irregular curvature which rendered it useless. But measurement showed that individual chips were about 1 cm away from each other, leading to modification of a standard drag bit (Fig. 18a). The finally chosen position of the drag bits in the individual tool holder is seen in Figure 15.

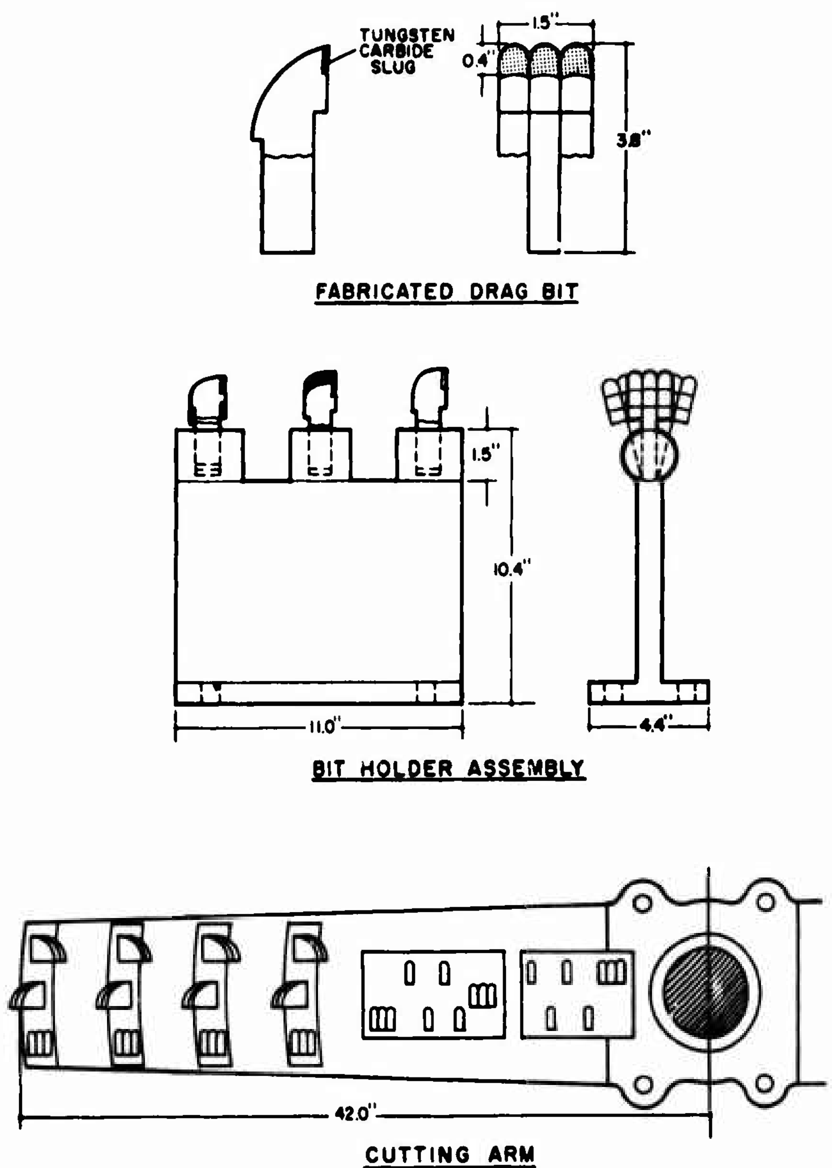


Figure 15. Cutting arm and individual tool holders.

Further observations were made on the wear of the teeth (Fig. 18b-e). When the tool moved in such a manner that its steel was not protected by hard inserts, it was quickly worn away (Fig. 18 b,c). Normally, wear rounded the cutting edge rather than chipped it (Fig. 18d), resulting in a progressively shallower cut and increased crowd demand. The hard inserts also wore unevenly. Figure 18e shows a hard inclusion in the tungsten carbide protruding because of differential wear.

The action of drag bits in homogeneous permafrost is shown in Figure 19. In an experimental slow cut a sharp bit was moved across a frozen sample (Fig. 19a). Its initial engagement produced a plastically deformed and compressed area (b), which, when motion was allowed to continue, increased until the first brittle chip failure occurred (c). The compressed area disintegrated immediately thereafter. A dull tool tended to "ride up" on the face, requiring much more crowd force to stay in the face and producing a large amount of smaller, plastically deformed chips

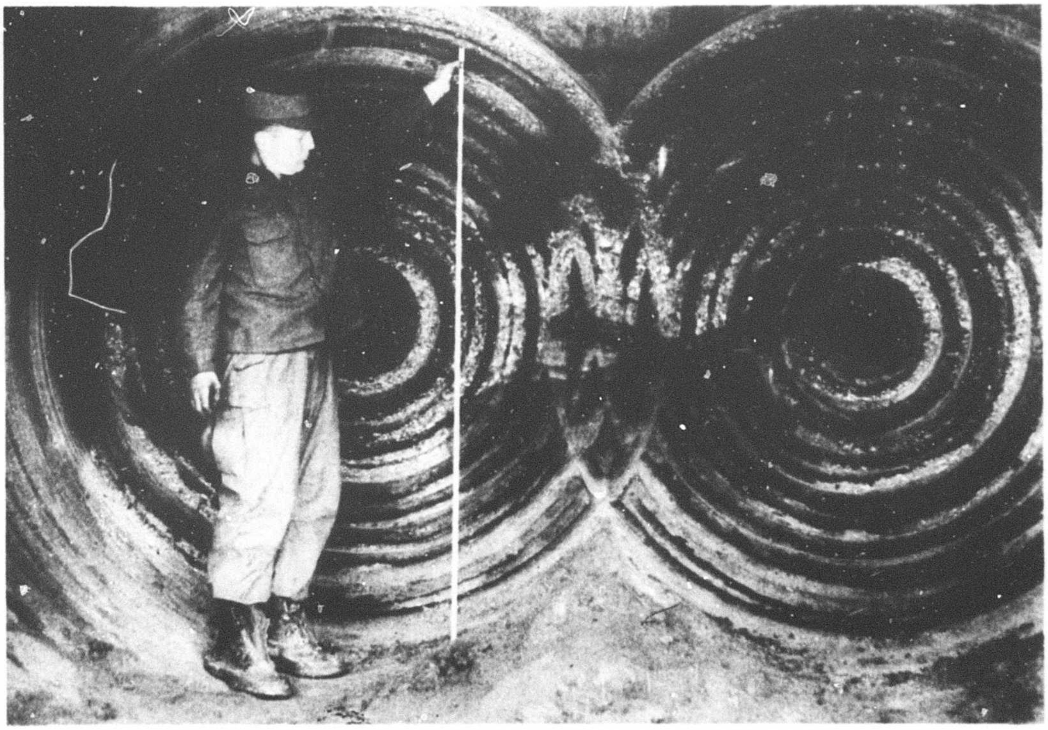


Figure 16. Face configuration consisting of cut grooves and lands. Gravelly part of tunnel.

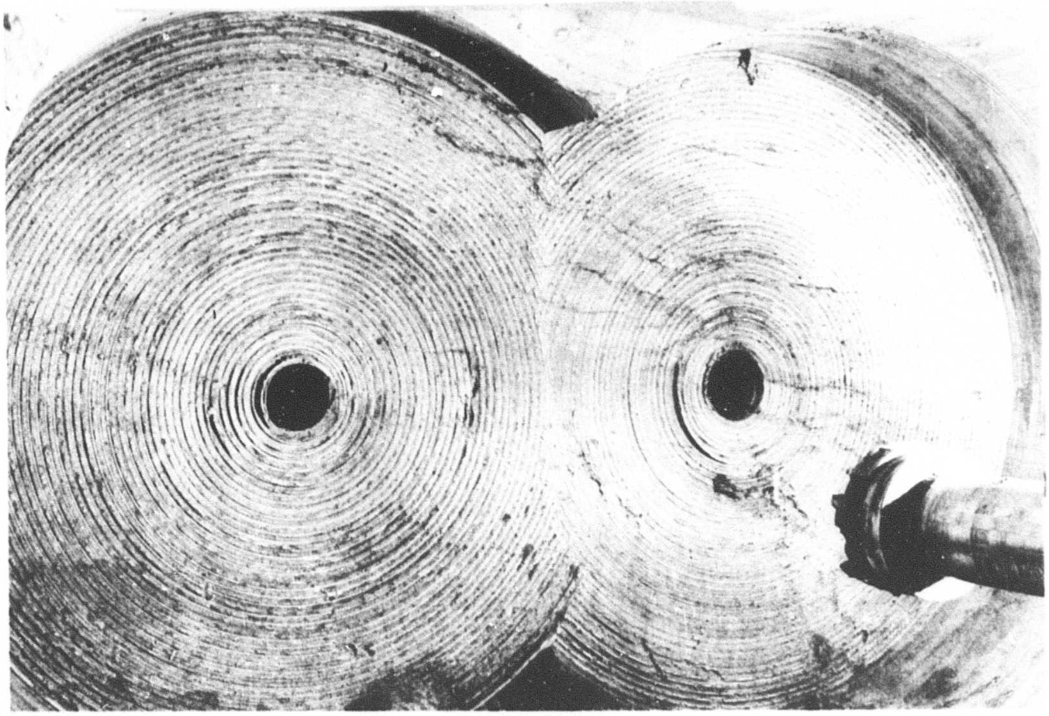
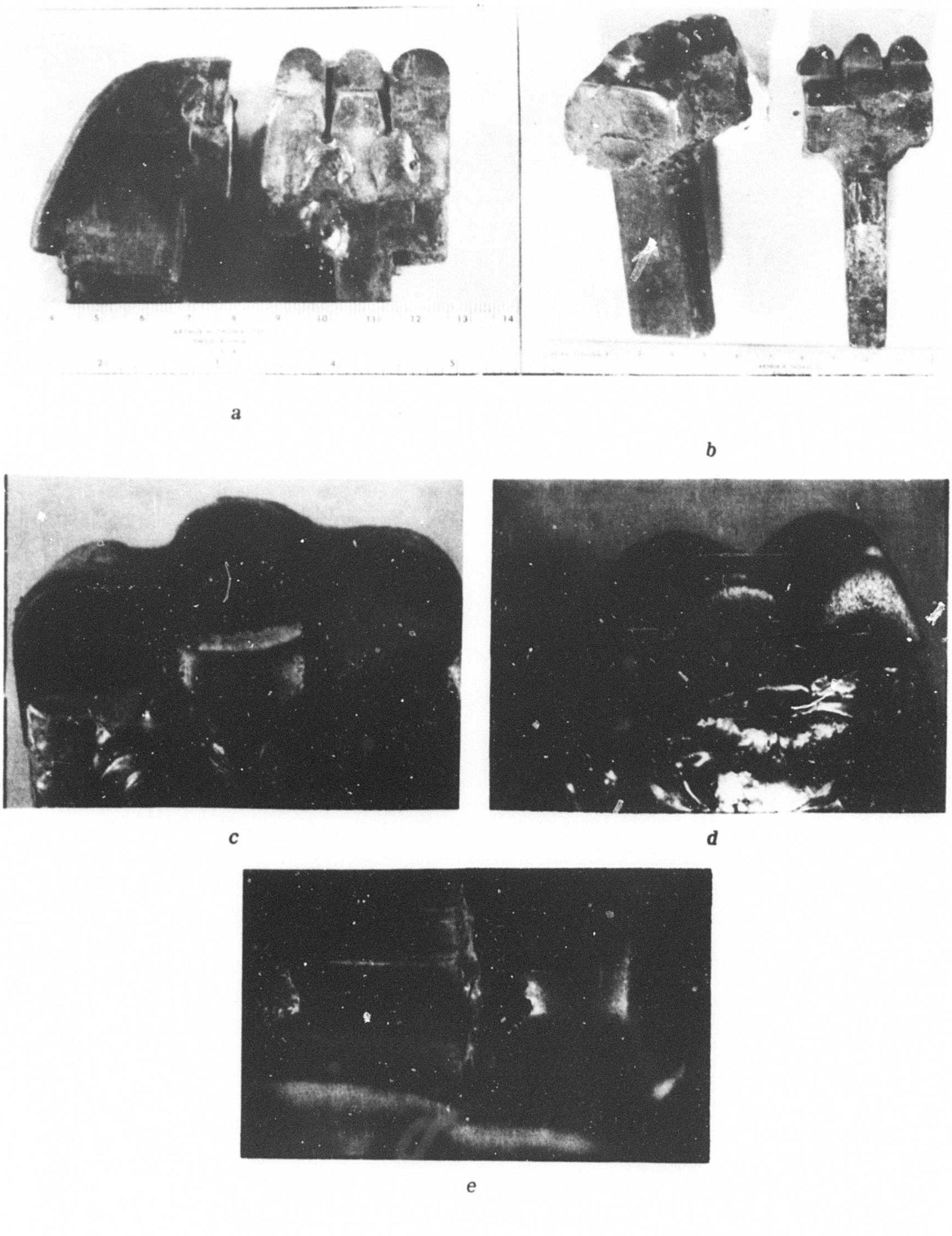


Figure 17. Full face cutting.



a b c d e

Figure 18. Triple edge drag bits.

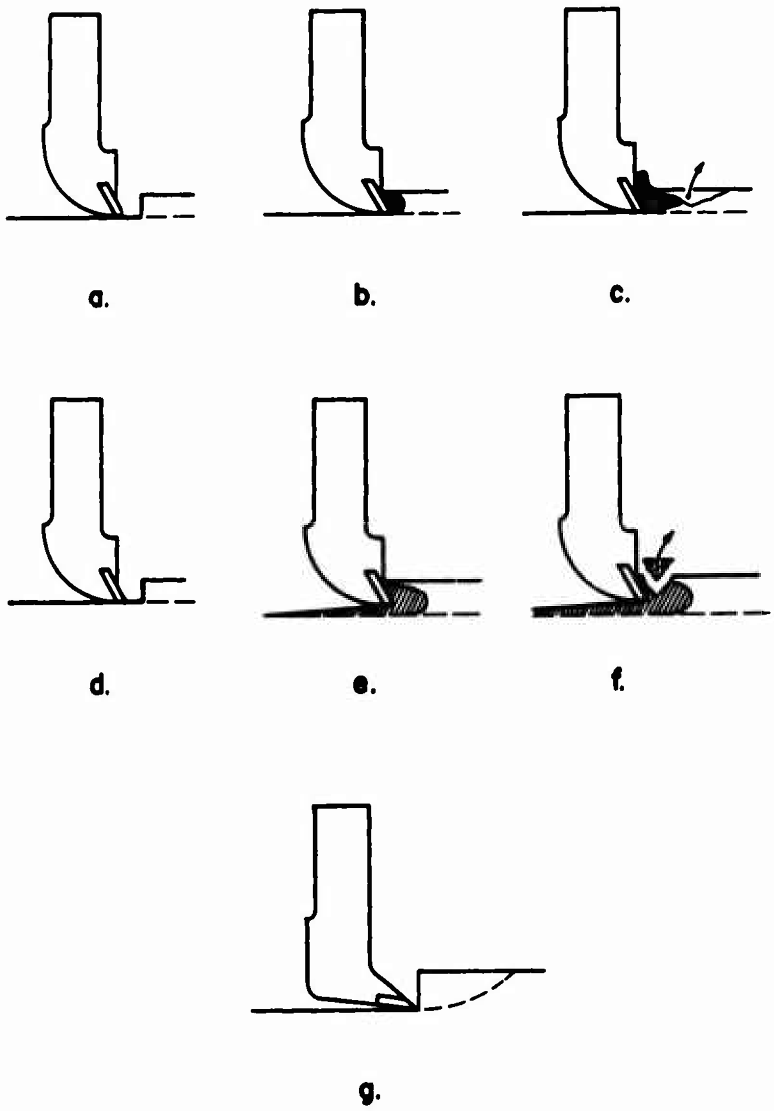


Figure 19. Drag bit action.

(Fig. 19d,e,f). Apparently a tool formed like that shown in Fig. 19g, or similar, would work better than standard drag bits. Discussion of the property and shape of the dotted line in Figure 19g as well as additional considerations on the process of cutting frozen ground evolved into a research program beyond the scope of the present paper.

Properties of permafrost tunnels

Plastic behavior and mode of failure. It is often said that permafrost is a rock material formed from any soil material by frost consolidation of its pore water. From this mining engineer's classification of permafrost, one visualizes a large variety of properties dependent upon temperature and composition. Properties of a large variety of permafrost types are compared on the following pages with similar rocks cemented by means other than freezing pore water.

As a cement, ice is weak and under sustained load is subject to greater plastic deformation than are cementing agents like calcite and dolomite in sandstone and conglomerates. A subsurface excavation in sandstone, siltstone or conglomerate becomes subject to brittle roof failure before any measurable plastic deformation occurs. But pillars in permafrost fail plastically and such a phenomenon as rock burst is unthinkable in permafrost tunnels over the whole range of natural temperatures.

Our own observations of deformation in frozen matter began with ice tunnel deformation in the massive ice of the Greenland Ice Cap (Swinzow, 1962). It was found that clean ice may deform slower than mixtures of frozen rock debris. Further observations indicated some types of permafrost with little or no plastic deformation: In three years a room of 65-ft span, dug in cold, bouldery, unsaturated (approximately 25% moisture) permafrost, did not deform in excess of measurement error. Permafrost of coarse material with dense packing does not readily deform plastically. Conversely, fine grained, supersaturated permafrost especially at high temperatures has a tendency to deform plastically. It appears that the solid soil particles weaken the ice. Observations at the Alaska Experimental Permafrost Tunnel (Fig. 20) showed noticeable deformation with only a small amount of overburden. Since the tunnel was dug under only gently sloping terrain, the perceptible difference in deformation rates could be tentatively explained only by the temperature difference between the middle of the tunnel and a point toward its work face or portal. The permafrost temperature difference between the two points was close to 1C while air temperature differences varied during the observation period, the point at 350 ft always being warmer.

The plastic behavior of local permafrost as well as experiments with explosives indicate that brittle roof failure is improbable under the influence of high velocity shocks such as large explosions at the surface. Although often weaker than materials cemented by other means, permafrost provides a safer roof under certain overburden and span conditions (Livingston, 1960).

Ground temperatures around a large cavity change with time. If the opening of the cavity is higher than its main space, its temperature will decrease and be lower than the annual average. Conversely, caves with a main room above the entrance are warmer than the mean annual temperature. In the first case, the cold winter air settles down in the cave and is not readily removed during the summer. As soon as the outside temperature becomes lower than that of the cave, air exchange begins. This is how so-called ice caves form in moderate climates. This effect, useful as it is, is not being utilized sufficiently at the present time.

A nearly horizontal opening in permafrost is subject to air currents that reverse their direction with the change of seasons. Anemometer observations in the Alaska Tunnel indicated that in the winter the relatively warm air moved along the roof toward the portal with maximum velocities reaching 2.5 km/hr and was replaced by cold air moving in along the floor. The simple measure of closing the portal tightly and reducing the inside activity to a minimum in the summer was sufficient to accumulate some heat sink capacity.

Artificial ventilation was inadequate since the air forced through the pipes arrived at the end of the tunnel several degrees warmer than the outside temperature. After the final excavation season a vertical shaft was drilled at the end of the tunnel. During the cold winter months it provided a strong chimney effect with rapid air exchange and effective cooling. The air circulation in the closed tunnel is limited to vertical convection between floor and roof.

Sublimation. Stable ice can exist in contact with air only if the air is saturated in respect to ice molecules. In cases of dry air (low relative humidity), ice "dries out." Sublimation is well understood and studied; its rates depend upon interface shape and ice vapor pressure (and therefore temperature). If at a given temperature and low air humidity, sublimation produces an increased amount of vapor in the vicinity of the interface, free air movement adjacent to it removes

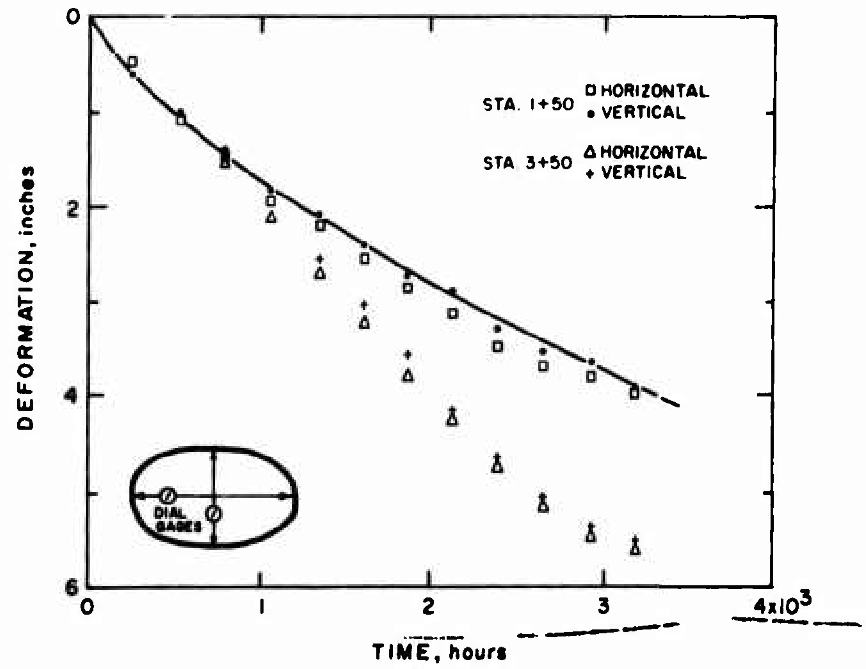


Figure 20. Relation of time to deformation at sta. 1+50 and 3+50.

the vapor concentration gradient, thus keeping the process of sublimation at a constant, rather than a decreasing, rate.

Permafrost surfaces, consisting of many solid particles of soil alternating with ice, are also subject to sublimation. In the tunnel a smooth, firm, freshly cut surface became dusty after a short time. The thickness of the dry layer increased rapidly, reaching 1 to 1.5 cm in a week. The layer was firm but very friable and strong air currents disturbed it and made the tunnel air dusty.

The rates observed in the field, as well as those reproduced in laboratory studies (Luyet, 1967), could not be made to correspond to any rigorous prediction. In the field, temperatures, air humidities and ventilation rates changed almost hourly. Since one purpose of the laboratory work was to set up a standard condition close to the average natural one, tests were conducted at -2C and 50% relative humidity. The tests revealed that the permeability for water vapor was constant and that sublimation occurred at decreasing rates. The increased thickness of the dry shell was apparently the main factor bringing the process to a halt. Observations in the tunnel indicated that an undisturbed dry dust shell may reach 14 cm in about 65 days, by which time the process is slowed down to an imperceptible rate.

Earlier work on prevention of sublimation from frozen ground surfaces revealed that simple measures such as spray painting, lacquering or coating with a non-drying petroleum product were sufficient to arrest the process fully over a period of five years (Swinzow, 1964).

Causally unrelated but intricately connected with sublimation is the process of hoarfrost formation in a closed permafrost tunnel with very little outside air entering and only limited human activity underground.

The Tuto, Greenland, permafrost tunnel is an example. The lower part of the tunnel is drying out by sublimation while hoarfrost grows in thick layers of crystals all over the upper part. The tunnel is dug on a gentle rise and the sharp demarcation line between drying and deposition is horizontal. In the portal area it is about 0.75 m above the floor and merges with the floor at 164 m. The continuously growing masses of hoarfrost crystals on the roof fail under their own

weight and land on the floor where they are subject to sublimation. This circulation of moisture is another check of sublimative drying of permafrost below the horizontal dividing line. Observations using ammonia fumes as markers revealed convection of air between roof and floor, the upward stream being in the middle of the tunnel. Apparently, it is a double convection cell with a maximum flow velocity of 0.7 m/min.

Similar phenomena will probably be observed in the Alaska tunnel when active research ceases and forced ventilation is discontinued.

SUMMARY

Military uses of an excavation in permafrost

Previous investigation has indicated that frozen ground responds poorly to disintegration by all types of explosive application. In subsurface exploration it is the poor powder ratio; in surface blasting it is the low yield and only moderate effect of bombing and artillery (Livingston and Waldron, 1965).

~~Most important,~~ however, is the specific response of roofs in subsurface excavations to blasts set off at the surface. The danger of brittle roof failure is, in the writer's opinion, minimal since brittle response of permafrost during short duration loading occurs only over a limited range of stress. Unless a shelter in permafrost is very shallow, so that overburden thickness is close to span width, brittle roof failure is unlikely as long as the roof contour is outside the direct fracture zone of the explosion.

Observations in Greenland conducted on cold, bouldery permafrost with a span of 20 m demonstrated a lack of response to explosive shocks from the surface as well as free blasts inside the tunnel.

The flexibility with which the frozen state may be put to use in excavations is also attractive for military purposes. Using a type of "concreting masonry" work, repairs of all sorts may be successfully performed in permafrost tunnels (Swinzow, 1964). Should roof crevices form in the process of excavation, they are easily repaired by use of a sand-water grout, which freezes back, rendering the needed strength and safety. Where plastic deformations are taking place, such as the present tunnel, they either could be accounted for in advance, or arrested by artificial means (such as chilling by winter ventilation).

Ease of excavation is another attraction for military use of tunnels in permafrost.

It has been demonstrated that a comfortable personnel shelter can be constructed in a cave dug in a frozen material. Russell (1966) described in detail an experiment where an insulated camp with all facilities was constructed in an ice tunnel in the Greenland Ice Cap. With sufficient insulation, room temperatures inside the shelter structure can be kept well above those outside. With sufficient ventilation the maintenance of low temperatures in the tunnel outside the building is not a serious problem. The construction of large command posts, bulk fuel storage caves, and warehouse facilities in permafrost appears to be feasible and should be investigated.

Tunneling method

The most striking feature of the Alkirk Miner is the novel pilot pull principle with its advantage of less weight and incipient increased maneuverability. The machine also has relatively low power consumption compared with other continuous mining systems. The rates of cutting obtained were promising. To be practicable, the principle must be applied with compatible,

reliable equipment. Modifications of the machine for use in permafrost should include redesign of the hydraulic system, vertical and horizontal control and tramming method, an improvement in anchoring and a heat exchanger.

Cutting speeds are insufficient for the perennially frozen silt. The design of the drag bits also requires consideration although the same bits used on a faster cutting machine performed better regardless of advanced wear (see Fig. 21). It appears that the design of special bits (perhaps such as suggested in Fig. 19g) requires consideration of varying cutting speeds of the machine. The application of the pilot pull principle is highly recommended for possible future excavations in perennially frozen silt deposits.

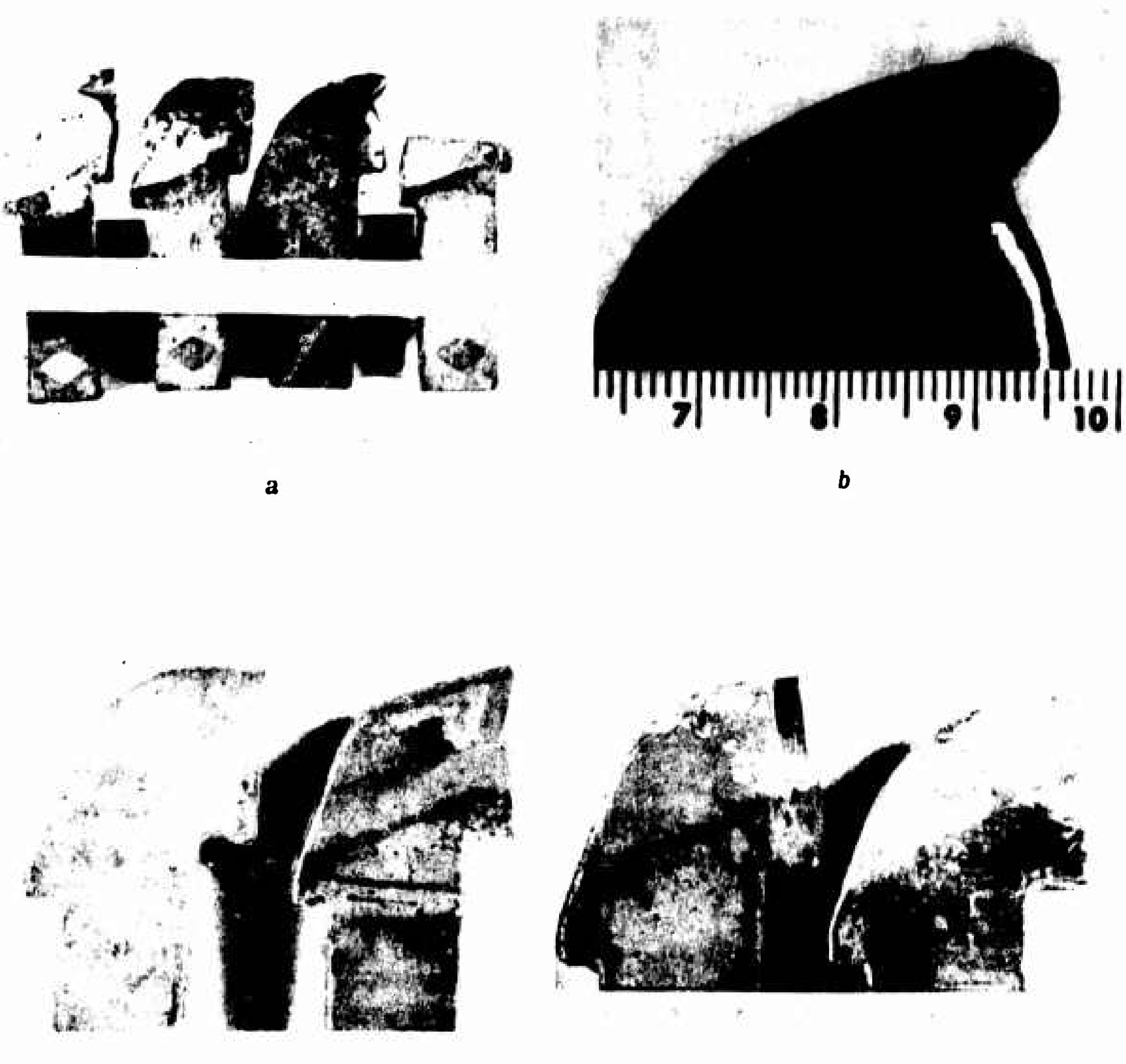


Figure 21. Chain saw teeth of the 10 RU miner.

Some reservations

The Alkirk Continuous Cycle Miner is a "first generation" machine originally developed for excavation in coal and soft rock. Its applicability to warm permafrost was the main purpose of the present application. For this reason, technicalities of construction have been kept to the minimum necessary to explain the principle, its advantages, and its weaknesses. The performance of the standard coal mining equipment used in the project may be stated as satisfactory, its detailed description is beyond the scope and need of the present study.

The overall conclusions were reached under the handicap of incompatibility of standard mining equipment with the Alkirk Miner. For example, the shuttle car used for debris removal (Fig. 9) was incompatible with the machine in two ways: it did not fit under the conveyor and its capacity to remove cut material was far less than the miner's ability to excavate, that is, to produce spoil. The mechanism employed between the two machines - the front loader - corrected only one deficiency, the dimensional incompatibility.

The Alkirk Miner had a low cutting speed and was armed with improper cutting tools. This necessitated excessive crowding which caused frequent anchoring failure. The need for refrigerated compressed air, frequent overloads, and failures in the hydraulic system were doubtlessly connected in part with the above conditions. It is concluded that in order to use the machine to full advantage it should be thoroughly redesigned to a second or perhaps a third generation model.

Despite all reservations concerning performance during the tunneling experiment, it is recognized that the machine has a series of progressive features, its relatively light weight and low power requirement being not the only ones. The pull-in principle is revolutionary and is potentially advantageous. This is connected with possibilities of better maneuverability. Hydraulic drive will potentially provide infinite control.

It cannot be overemphasized that to make the machine work in permafrost, a large research and development effort would need to concentrate on steering methods (Fig. 14c,d,e), anchoring the pilots, improving heat removal, and toughening the hydraulic system. Increasing angular cutting velocity and, especially, designing cutting teeth adapted for the various linear cutting velocities appear to be important.

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APPENDIX A

OBSERVATIONS ON A 10 RU COAL MINER

In addition to the investigation of the Continuous Cyclic Mining System described in the text, a standard 10 RU Mining Machine was subjected to a brief test. The machine is normally used in long-wall coal undercutting and in other specialized underground work.

The Joy 10 RU Cutter is a self-propelled, cable laying, tire-based machine working on a chain saw principle. It is powered by two motors: a 30-hp motor driving the hydraulic system and a 50-hp motor driving the chain saw. Both are 440-v ac.

The machine has a variable tram speed, the maximum being 70 m/min. Its cutting speed of 183 m/min was successful, in the way permafrost disintegrated.

One advantage was the extreme simplicity of operation – the 10 RU could be operated successfully after only a few hours of training.

The versatility of the machine permitted its use for a variety of functions such as trimming the tunnel profile to a desired shape, cutting notches in the wall of the tunnel for cable and pressure hoses, and excavating large rooms with flat walls.

Although the purpose of the machine is not tunneling, an attempt to do so was successful. The machine was used in a discontinuous cycle, e.g. about 2-m-deep cuts were made at first vertically along the edges of the face and then horizontal cuts were made every 20 cm beginning at the bottom. In this way, the face advanced 2 m per cycle after the front loader and shuttle car removed the debris.

The chain of the machine was armed with drag bits essentially of the same size and configuration as those in the Alkirk Miner. Apparently due to the high cutting velocity, the 10 RU produced debris that was more uniform and of coarser size than that produced by the Alkirk Miner. While particles liberated by the teeth of the Alkirk Miner were between 2 mm and 1 cm, and the whole muck pile contained a large amount of dust, the cuttings produced by the 10 RU were from 3 to 7 cm in size with a very small amount of dust, indicating a more efficient operation.

Correspondingly, the expansion factor in the muck pile of the 10 RU Miner was found to be low (1.8) compared with that of the Alkirk Miner (2.45).

Observations on the wear of cutting teeth together with the material removed indicate that the Alkirk machine "cuts" by slow induced failure; the faster 10 RU cutting speeds ensure brittle failure with all its advantages. Furthermore, since the expansion factor could be kept smaller with the 10 RU, its cutting process seems to be more advantageous. (It is emphasized that a lower total specific surface of the cut material is always advantageous.) Since the latter parameter is in direct relation to expansion factor, special observations were not needed.

Also of interest is the low dependency of the machine's performance upon the condition of its teeth. While the progressive wear of teeth on the Alkirk machine during the slow cutting was accompanied by increasing crowd demand and higher packer pressure with all its consequences,

partial or full loss of cutting edge of the teeth of the 10 RU produced virtually no adverse effect on performance.

Figure 21a shows the normal sequence of tooth wear in the Fairbanks silt. The last tooth performed as well as the others did. Figure 21b shows an enlargement of the third from left tooth indicating its mode of disintegration.

In some cases, defective manufacturing resulted in absence of clearance (Fig. 21c) but subsequent wear corrected the situation.

Sometimes improper insertion of tips resulted in poor performance (Fig. 21d). For example, one tooth with a poorly set edge, all others being proper, generated enough vibration to disengage the saw from permafrost.

PRODUCTIVITY OF OPERATION

Since the construction of the tunnel was not the sole purpose of the research (neither was a test of the machine *per se*), a precise prediction of its efficiency is impossible.

The tunneling equipment had to be engaged in tandem (see Fig. 9). The Alkirk Miner, on the extreme right, combined two functions, cutting the face and elevating the cut material with its conveyor. Since the shuttle car would not fit under the Alkirk Elevating Conveyor, the Joy Front Loader had to be switched in between. Finally, the dump conveyor-equipped shuttle car picked up the material and transported it to the muck pile.

The equipment was supplied with power as shown in the left diagram of Figure 9. The right diagram shows the routing of compressed air to the miner and venturi pump (not shown) used to evacuate warm air from the machine. In addition, there was a string of lights and a field telephone close to the face connected with the powerhouse and outside.

This set-up was partially described in the main text. Accurate prediction of production performance is difficult but during the report period the machine produced 63 m of tunnel in 21 hours of operation.

The performance of the equipment was observed and data collected in order to detect possible weaknesses. All malfunctions and breakdowns were noted and categorized (Table AI). An indicator of the extent of failures is the down-time during repairs.

Rebuilding and redesigning certain components of the machine would undoubtedly improve the function of others. For example, a better design would eliminate packer slip; elimination of hydraulic hammer effects would result in elimination of many component failures.

All mining was accomplished within 30 9-hr shifts. Since six production personnel were employed on the average, a total of 1620 man-hours was to account for productivity determination. Besides the 910 man-hours spent on repair of mining equipment and 208 man-hours on mining, a total of 50 man-hours were spent on maintenance.

Table AII gives a breakdown of manpower utilization. Note that the total number of work hours (time) is larger than time available, since most of the activity in maintenance proceeded simultaneously.

Table AI. Mining equipment failures registered during the tunneling operation (from shift reports)

Failure	*Repair time (hr)*
Alkirk Miner	
Upper cusp cutter:	
Axis shorn off	62
Torn drive chain	11
Shorn off support	9
	82
Hydraulic system:	
Line leaks and broken lines	32
Broken pumps and motors	47
Valve failures and air locks	27
	106
Mechanical failures in mechanisms:	
Torn thrust rings	9
Bends in pilot tubes	5
Broken packers	6
Torn tracks	8
Torn bit holders	12
	40
Elevating conveyor:	
Motor replacement	7
Realignment, tooth replacement, Rubber skirt replacement	2
	9
Miscellaneous:	
Front scraper blades bent	5
Operational failures without breakdown:	
Packer slipping	38
Cleaning plugged pilot tubes	3
Realignment of miner	30
	71
Shuttle Car	
Cable torn out	9
Cable insulation embrittled by frost	2
	11
Front Loader	
Frozen lines	2
Frozen conveyor	10
Broken gathering arm bearings	10
Hydraulic line failure	5
	27

Table AI (cont'd)

Failure	*Repair time (hr)*
Stationary Equipment	
Malfunctions in refrigerator	10
Power failures	3
	13
Total repair time:	364
Repair in man-hours	910

Table AII. Manpower utilization during 30 9-hr shifts of mining

	Time (hr)	*Labor (man-hr)*
Mining	33.6	207.6
Repairs (Table AI)	364	910
Maintenance		
Miner	143	370
Shuttle car	14	33
Front loader	24	58
Aboveground equipment	19	41
	597.6	1619.6
Available	(270)	(1620)

Besides illustrating the labor utilization pattern, Table AII indicates that a substantial reduction in only two items, repair and maintenance of the Alkirk Continuous Mining Machine, could easily improve its productivity (not mining rate) by at least three times.

The personnel operating the Alkirk Miner did not have any specialized training. It is felt that specially trained people would not be able to increase the productivity of the machine, but would be better than untrained people in making repairs and adjustments.

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13. ABSTRACT

A mechanical method of tunneling in permafrost was investigated by excavating the Alaska Experimental Permafrost Tunnel in a perennially frozen stratum of Fairbanks silt at the edge of a gold dredge field 11 miles north of Fairbanks. The tunnel is 360 ft long and about 7 x 13 ft in cross section. It was cut by the Alkirk continuous cyclic mining method. Certain properties of the frozen silt were investigated and the tunnel was evaluated as a shelter for military purposes. Temperatures, mechanical compositions and moisture contents are discussed and observations on plastic deformation are given. The machine uses a pilot-pull principle to provide face pressure. Its potential performance was evaluated. Special observations of cutting strain and power consumption were performed and the cutting process was analyzed. It was found that the mechanical process is expedient and that with modifications the Alkirk principle promises to become a feasible method of excavating deep shelters in permafrost. Subsurface shelters in permafrost provide advantageous protection against high velocity shocks. The operation's efficiency is analyzed in the appendix.

14. KEY WORDS

Frozen soil	Tunneling (excavation)
Shelters	Tunneling machines
Soil mechanics	

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